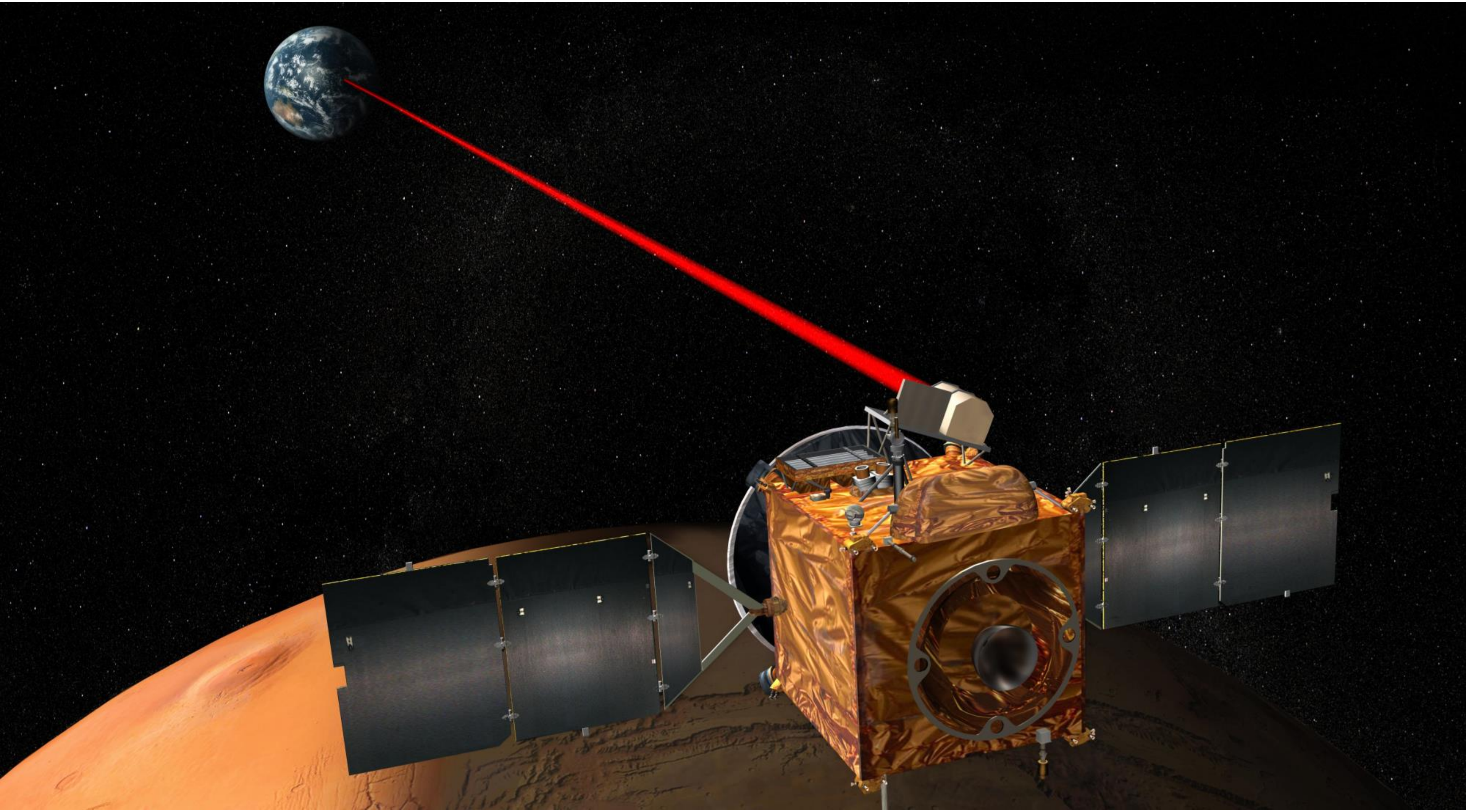


Spacecraft Navigation Using Optical Astrometry & Ranging

Tomas Martin-Mur

Workshop on Emerging Technologies
for Autonomous Space Navigation

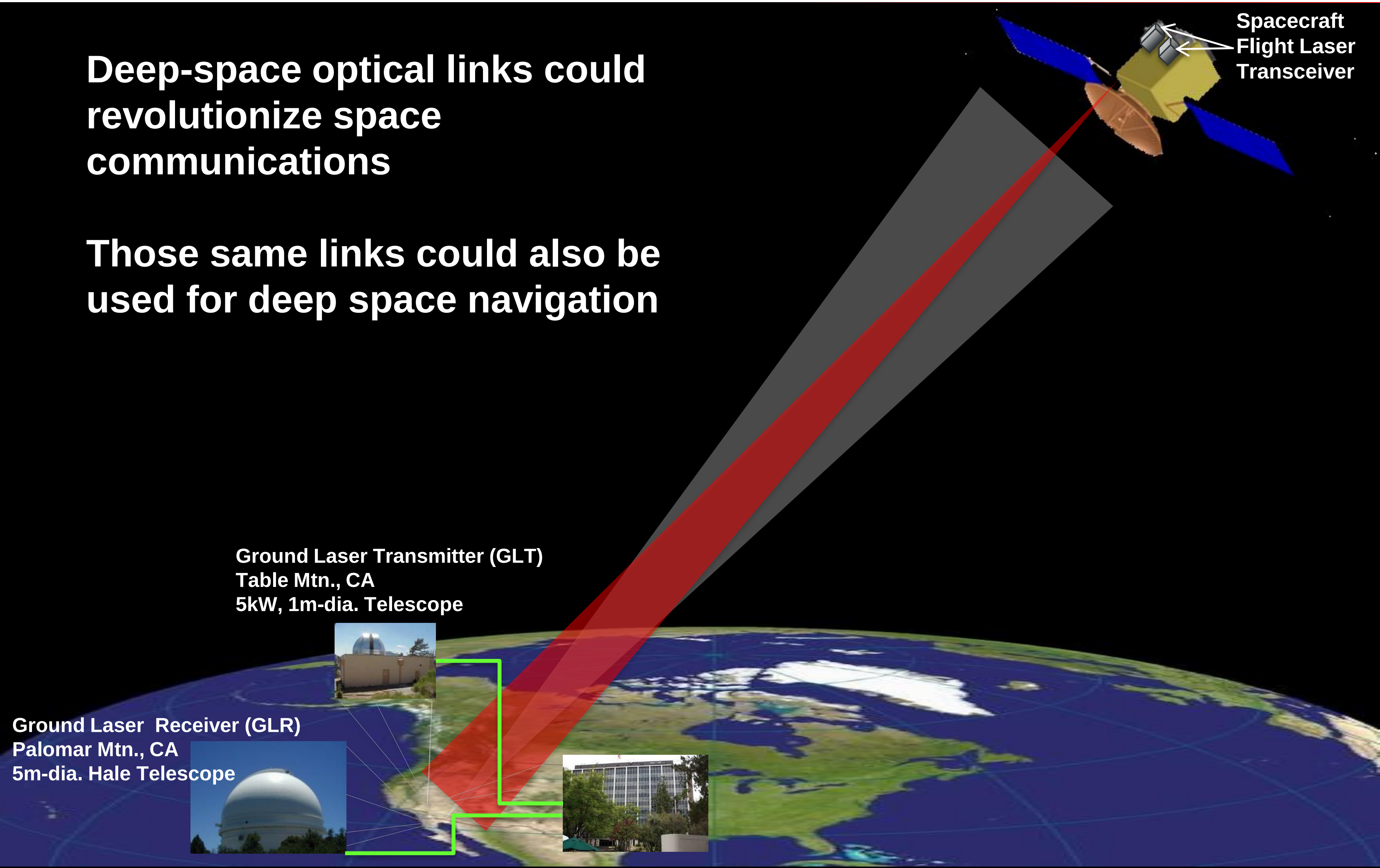
16 February 2017

Jet Propulsion Laboratory
California Institute of Technology

Opportunity: Optical Communications Systems

Deep-space optical links could revolutionize space communications

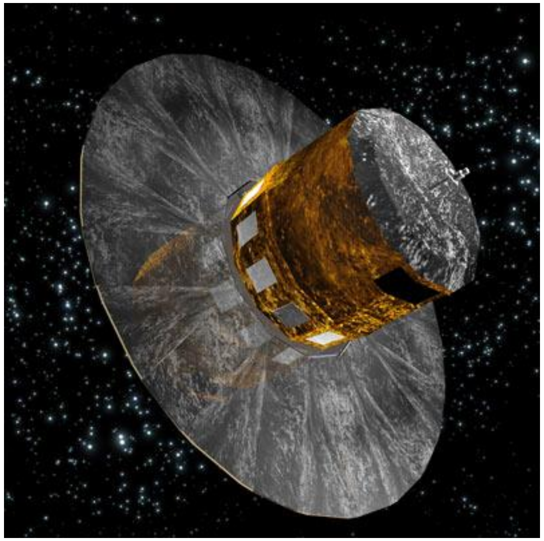
Those same links could also be used for deep space navigation



Opportunity: ESA's Gaia Star Catalog

Topic covered by Chris Jacobs

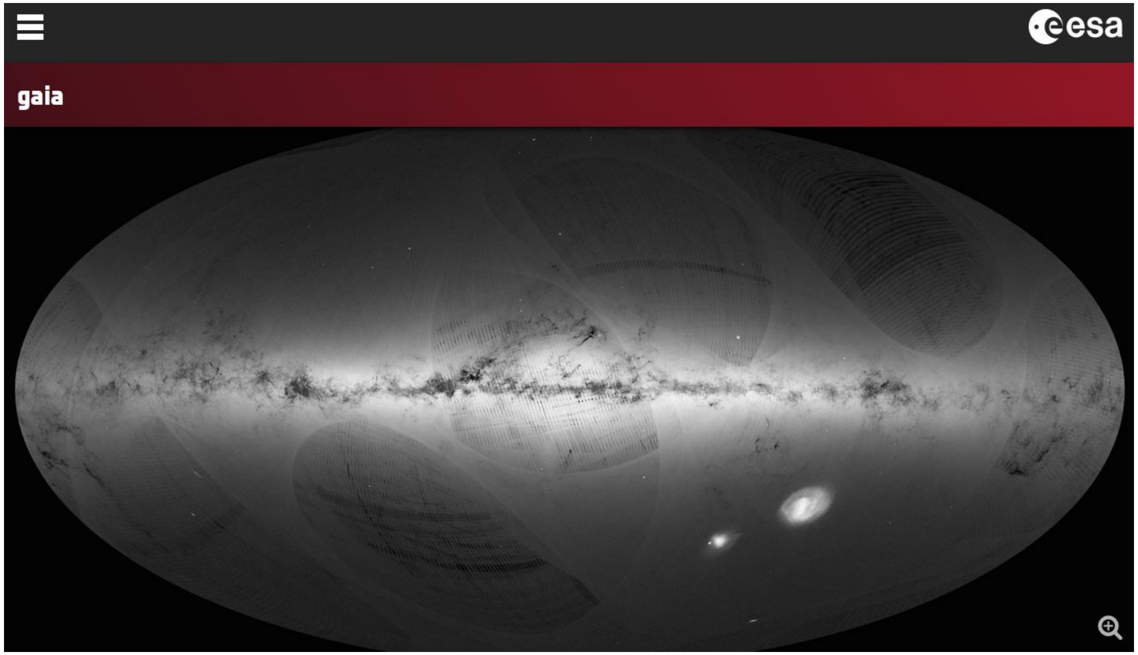
Will provide reference star positions than can be used to perform spacecraft astrometry at a level comparable to that possible with VLBI



The Gaia spacecraft
Image courtesy: ESA

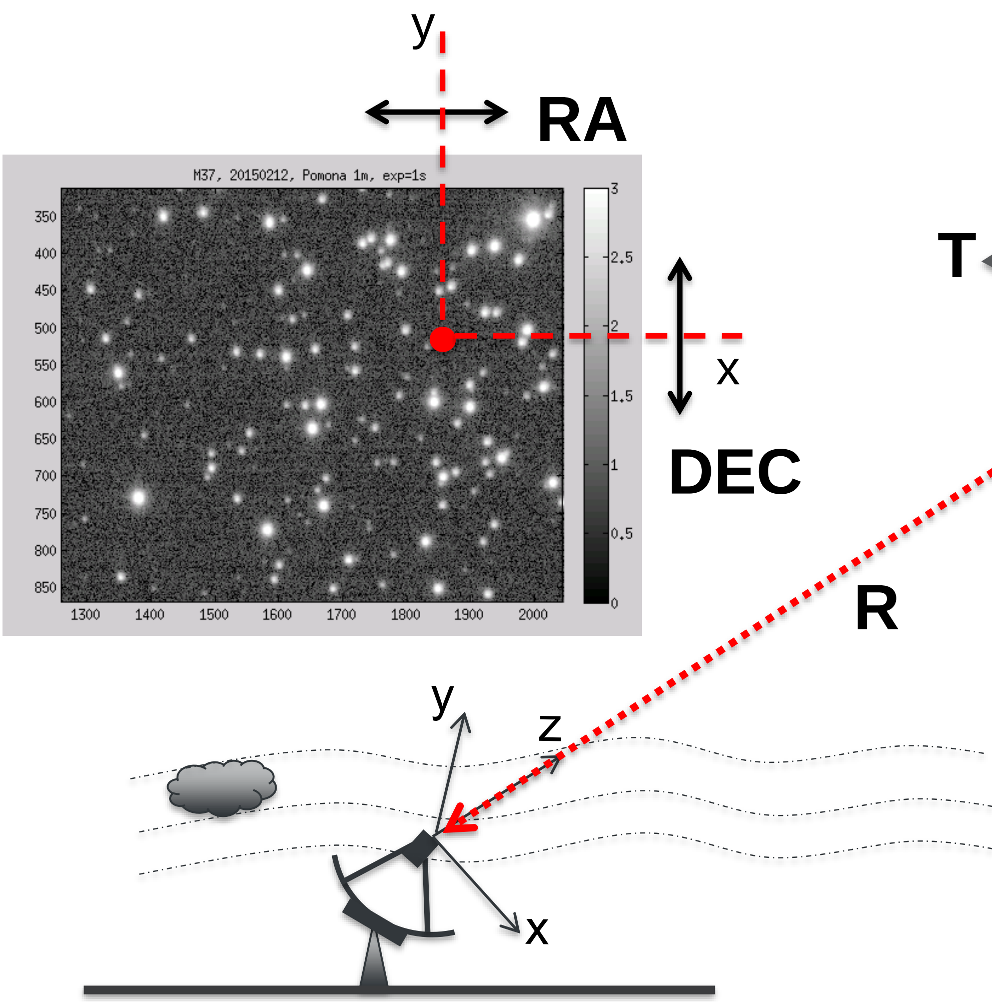
~37 million stars down to 15^m accurate to 0.12 nrad

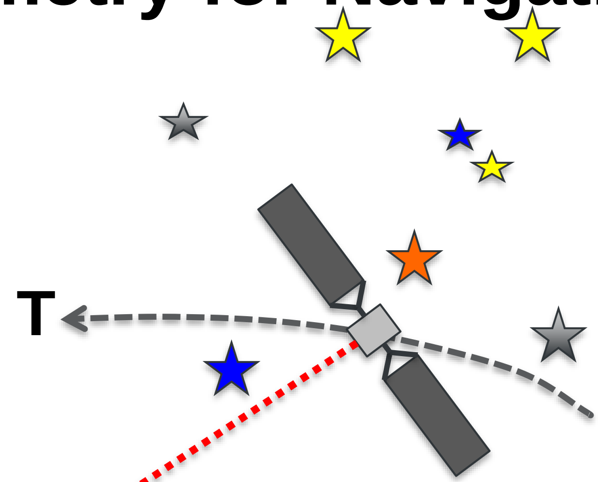
~1 billion stars down to 20^m accurate to 2 nrad



Gaia sources
Image courtesy: ESA

Optimetrics and Astrometry for Navigation





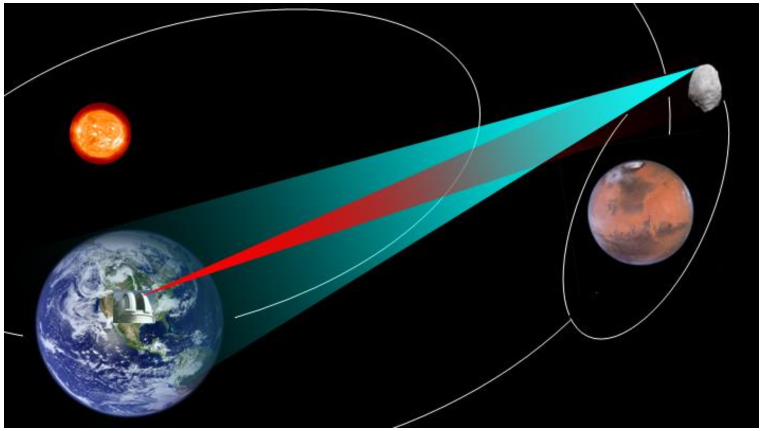
- **Spacecraft position components relative to telescope can be measured optically:**
  - **LOS Range (R) and Doppler (D)**
  - **POS Astrometry (RA, DEC)**
- **Background star locations req'd for pointing knowledge and frame tie**
- **Measurements processed on-board or on-ground to determine trajectory**

(x, y) define plane-of-sky (POS)
z defines line-of-sight (LOS)

Credit: Chengxing Zhai

Building block: Ground-based High-power Lasers

- High-powered laser for testing being installed at the OCTL
- It should allow for reflector-based astrometry and ranging up to lunar distances
- It can also be used for deep-space transceiver-based experiments



Credit: Slava Turyshev

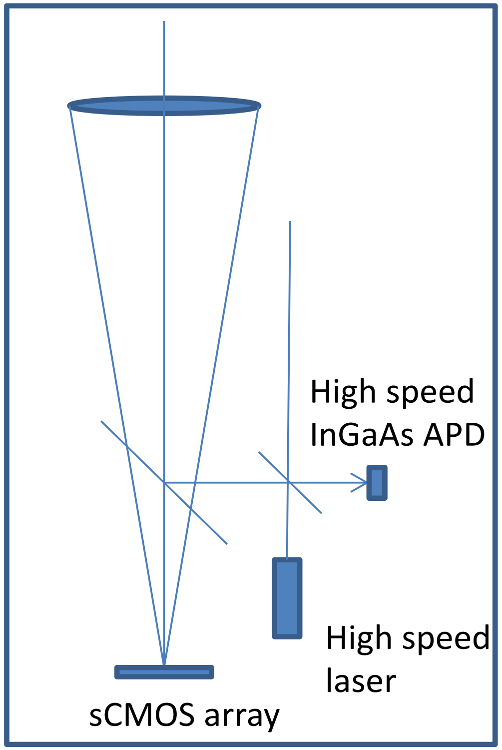
Building block: Spacecraft Optical Terminal

- Goals:
  - **Precision ranging (5 mm)** with high BW receiver & transmitter using accurate on-board time-tagging of sent and received laser-optical signals;
    - Either 2-way, or 1-way when equipped with a precise on-board clock
  - **On-board high-precision astrometry (10 uas)** with a large-format, multi-megapixel, low noise, fast CCD camera;
- Approach:
  - Build and demonstrate performance of proof-of-concept for new instrument capable of communication, ranging, and astrometry.

Credit: Slava Turyshev

On-board Astrometry

- On-board multi-megapixel CCD camera integrated into DOT would enable precision astrometry to ~20 μas
  - Beacon-less acquisition and comm (current DSOC needs an Earth-based optical comm beacon);
  - Autonomous nav relying on an over 10,000 increase in onboard astrometric capabilities;
    - » Using asteroids or moons as targets
    - » Using other laser-equipped spacecraft as targets

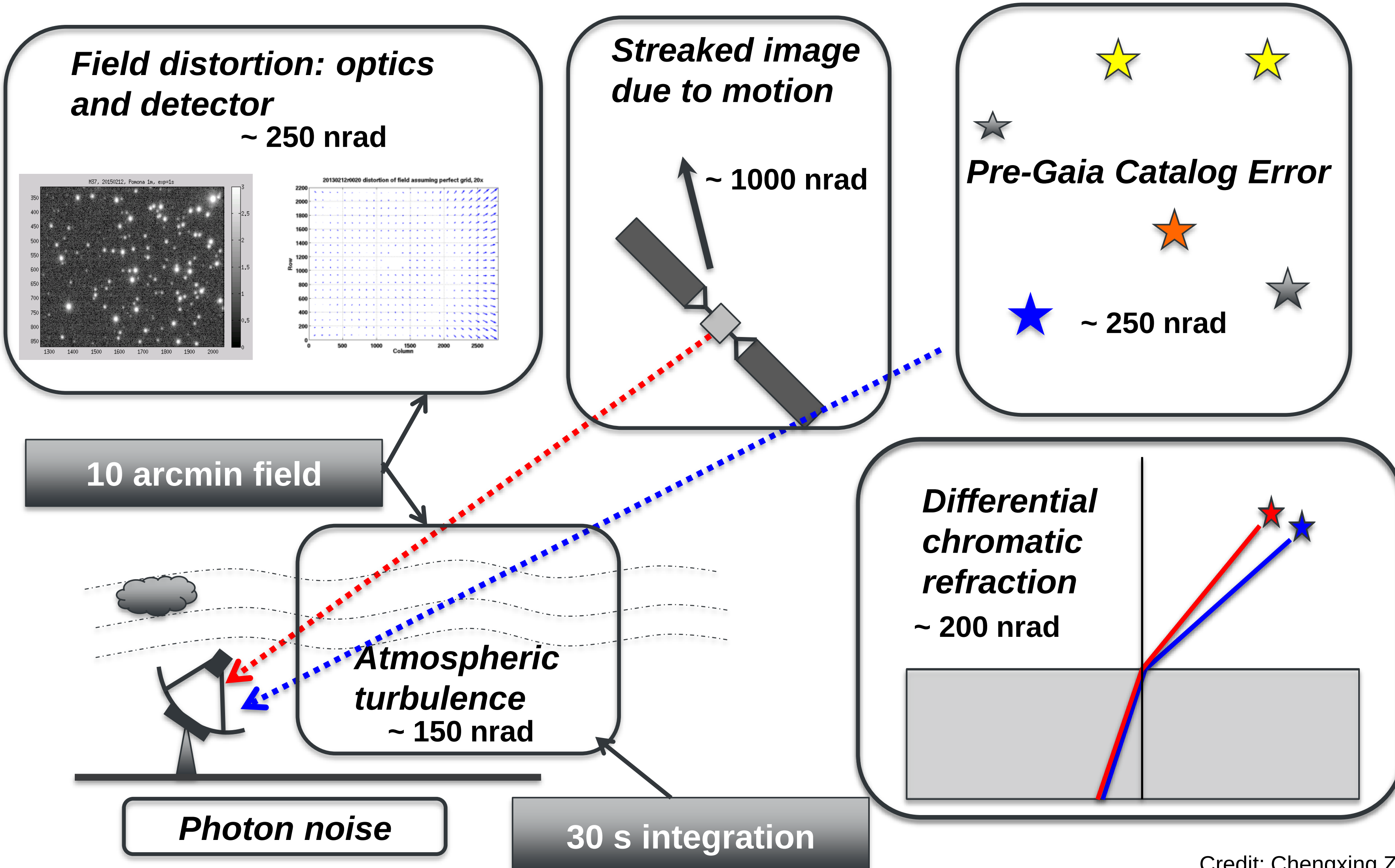


Credit: Slava Turyshev

Building block: Ground-based Telescopes and Detectors

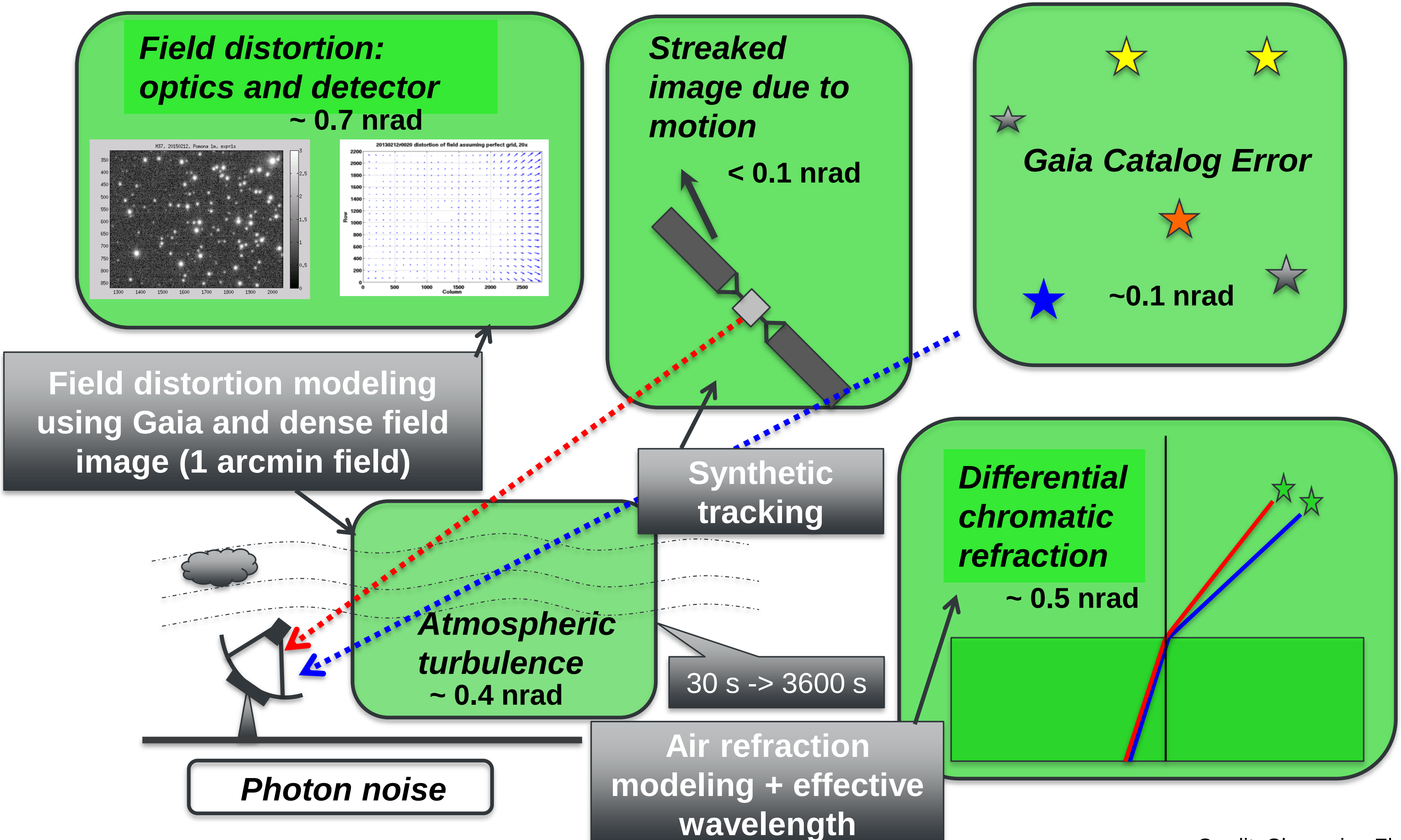
- 5 nrad spacecraft astrometry could be achievable with a 1 m telescope, and 1 nrad with a 5 m telescope.
- It may be more efficient to have two different types of ground telescopes, one for telemetry and ranging, and another for astrometry.

Point of Departure for Astrometry



Credit: Chengxing Zhai

Goal for Precise Astrometry

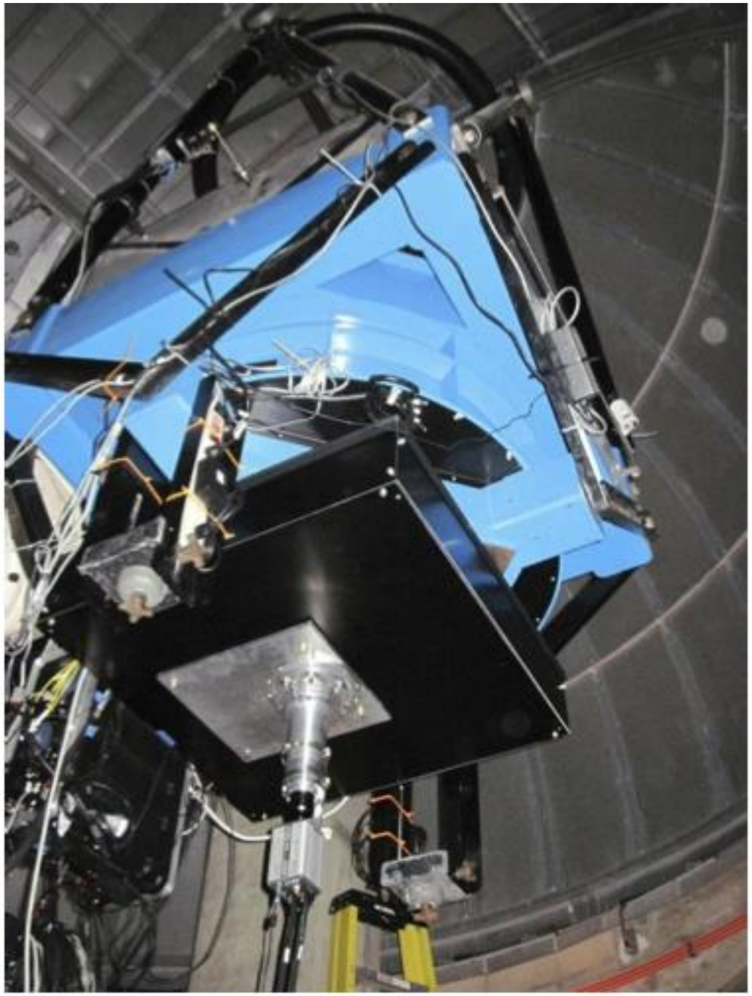


Credit: Chengxing Zhai

New Camera on Pomona College 1m Telescope a JPL's Table Mountain Observatory

- A new camera has been installed at TMO for precision astrometry and it is being calibrated using the 2016 release of the Gaia catalog.

- Currently being tested with asteroid observations.



Credit: Chengxing Zhai

Optical Comm Nav Pros and Cons

Pros:

- Single-station plane-of-sky measurements
  - Possible without changes to the spacecraft optical terminal
  - Feasible with smaller apertures

- Not affected by charged particles (ionosphere or solar plasma)
  - Solar plasma is the dominant error source for X-band tracking

- Improved ranging accuracy
  - Ranging requires changes to the spacecraft optical terminal

Optical Comm Nav Pros and Cons

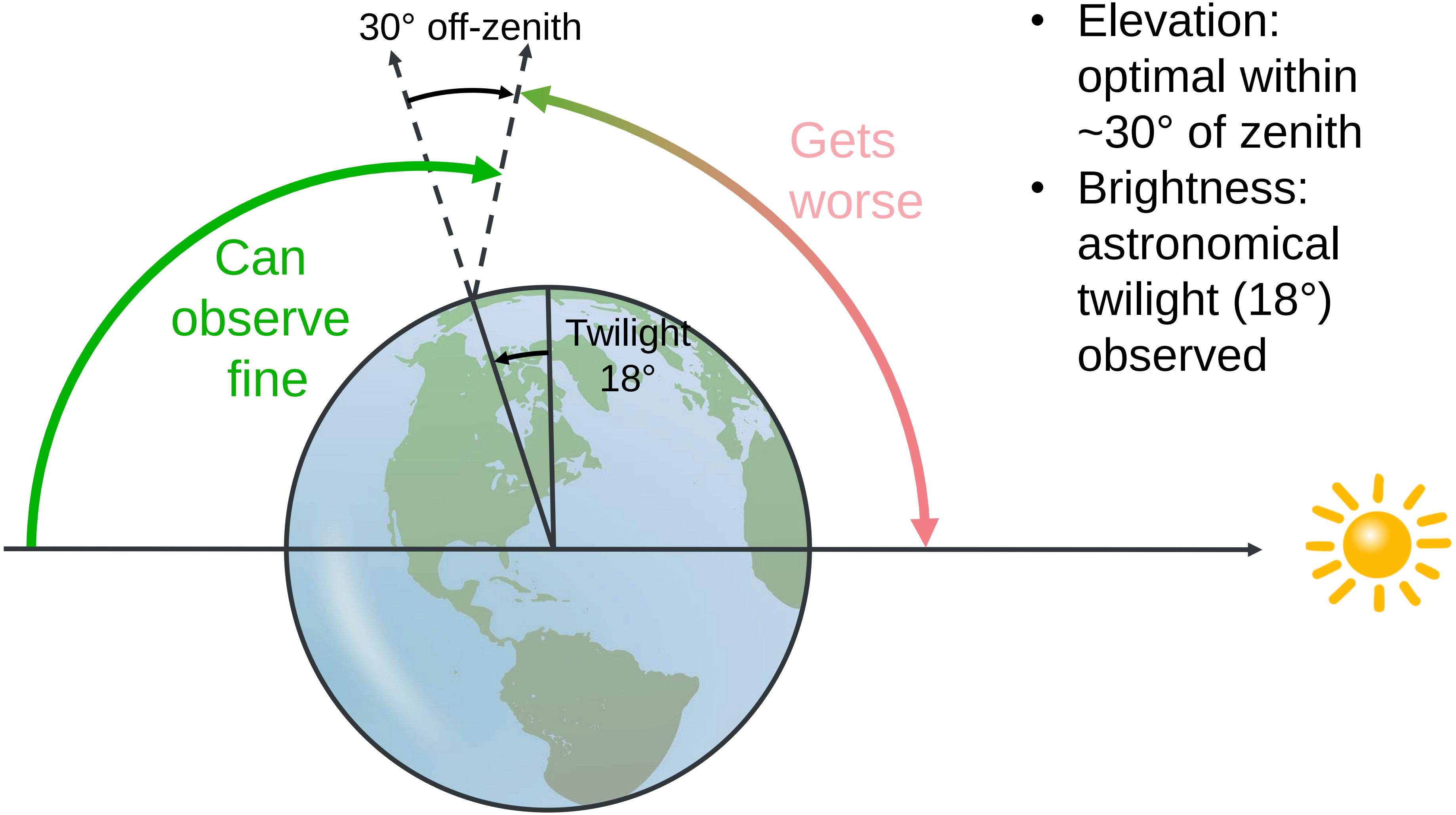
Cons:

- Ground-based optical tracking precluded by cloud cover
  - Could be mitigated by regional diversity

- Astrometry less accurate or impossible with increased levels of sky brightness
  - Astrometry not available for small Sun-Earth-probe angles

- Requires precise pointing, no optical LGA at deep-space distances
  - It may not be possible to track and operate the payload at the same time
    - Solvable with a gimballed optical terminal

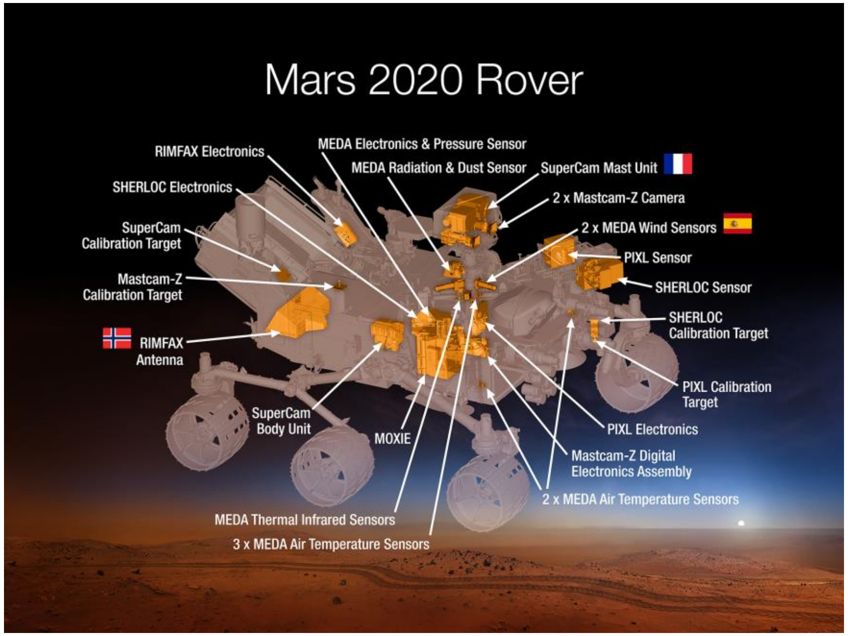
Optical Astrometry Constraints



- Elevation: optimal within ~30° of zenith
- Brightness: astronomical twilight (18°) observed

FY16 Navigation Analysis

- Radio and optical data types simulated
- Different mission scenarios considered
  - Mars lander case based on Mars 2020
  - Mars orbiter case based on MAVEN (Mars Atmosphere and Volatile EvolutioN)



Mars 2020 schematic. Image courtesy of NASA.

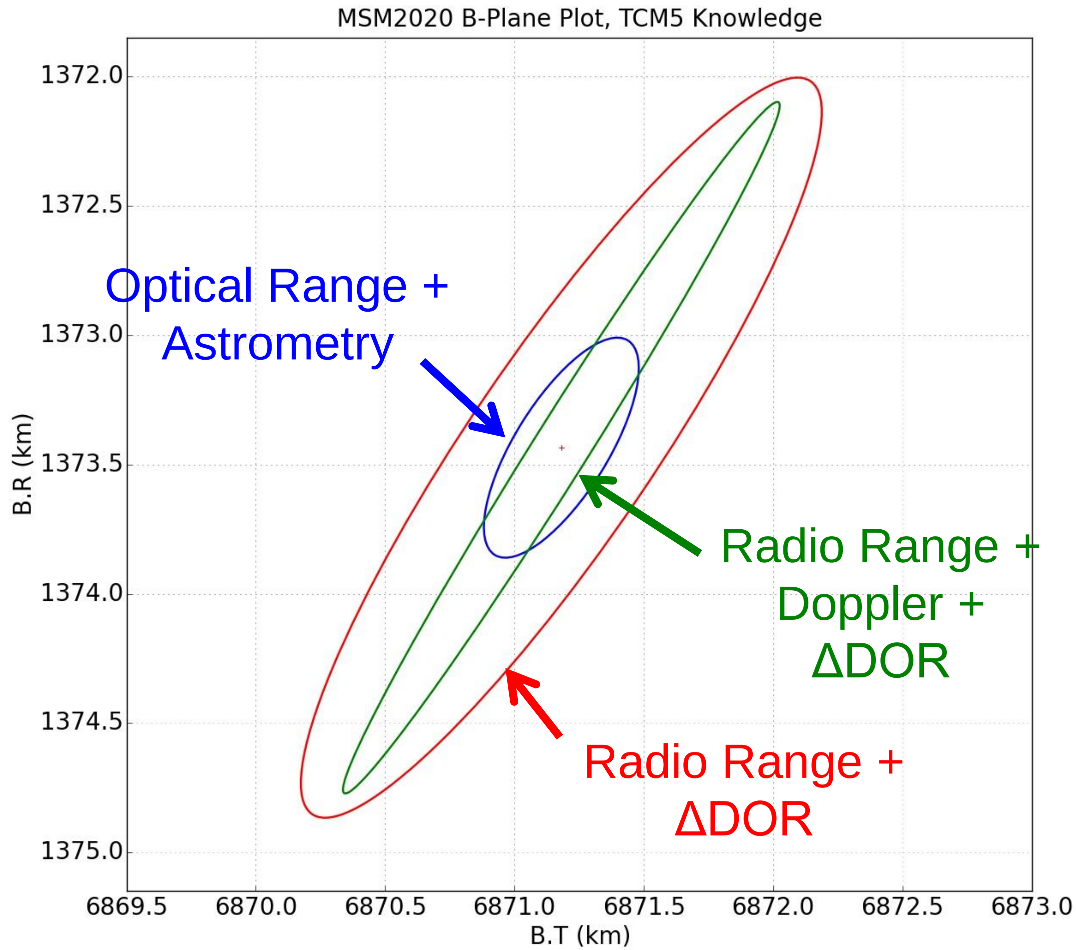
MAVEN at Mars. Image courtesy of NASA.

Comparing Radiometrics and Optometrics

	Radiometrics	Optometrics
Data Types	Two-way Doppler, two-way SRA range, ΔDOR	Optical range, ground-based astrometric measurements of angular position
Data uncertainties	Doppler: 0.10 mm/sec (0.00562 Hz) SRA: 21.0 RU (2.99 m) ΔDOR: 0.06 ns (2.25 nrad)	Range: 5 cm (360 sec integration time) Astrometry: Depends on elevation angle, sky brightness, angle between Sun, spacecraft, and Earth
Error sources	Earth orientation, station location, ephemeris, GMs, clock	
	Troposphere + Ionosphere	Troposphere only
	Quasar catalog	Star catalog

Mars Lander Results

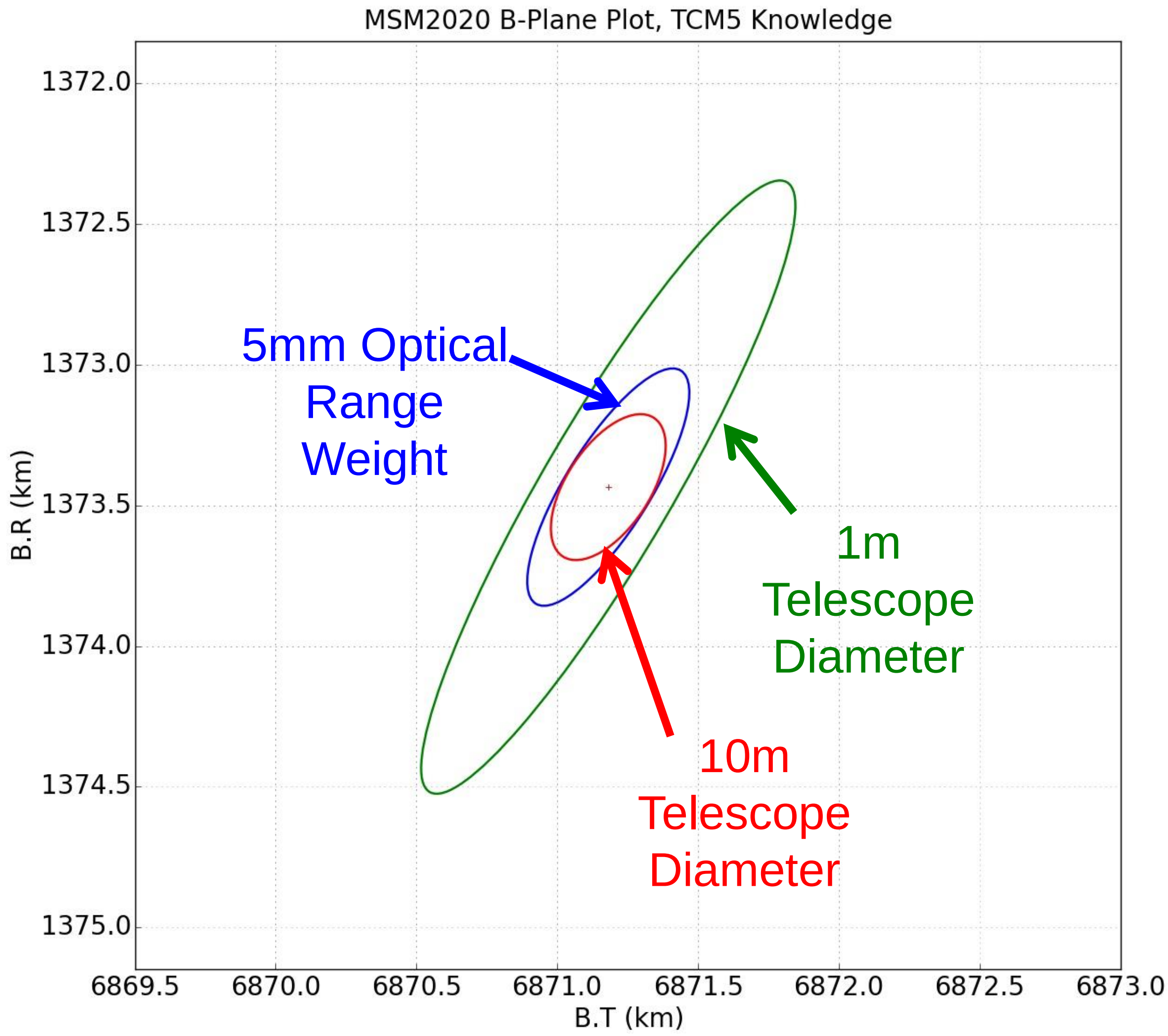
- Assuming continuous availability, optical can outperform traditional radiometric tracking data
- Optical outperforms direct radiometric analog (Radio range + ΔDOR)
- Could meet MSL, Mars 2020 requirements



Credit: Sarah Elizabeth McCandless

Mars Lander Results

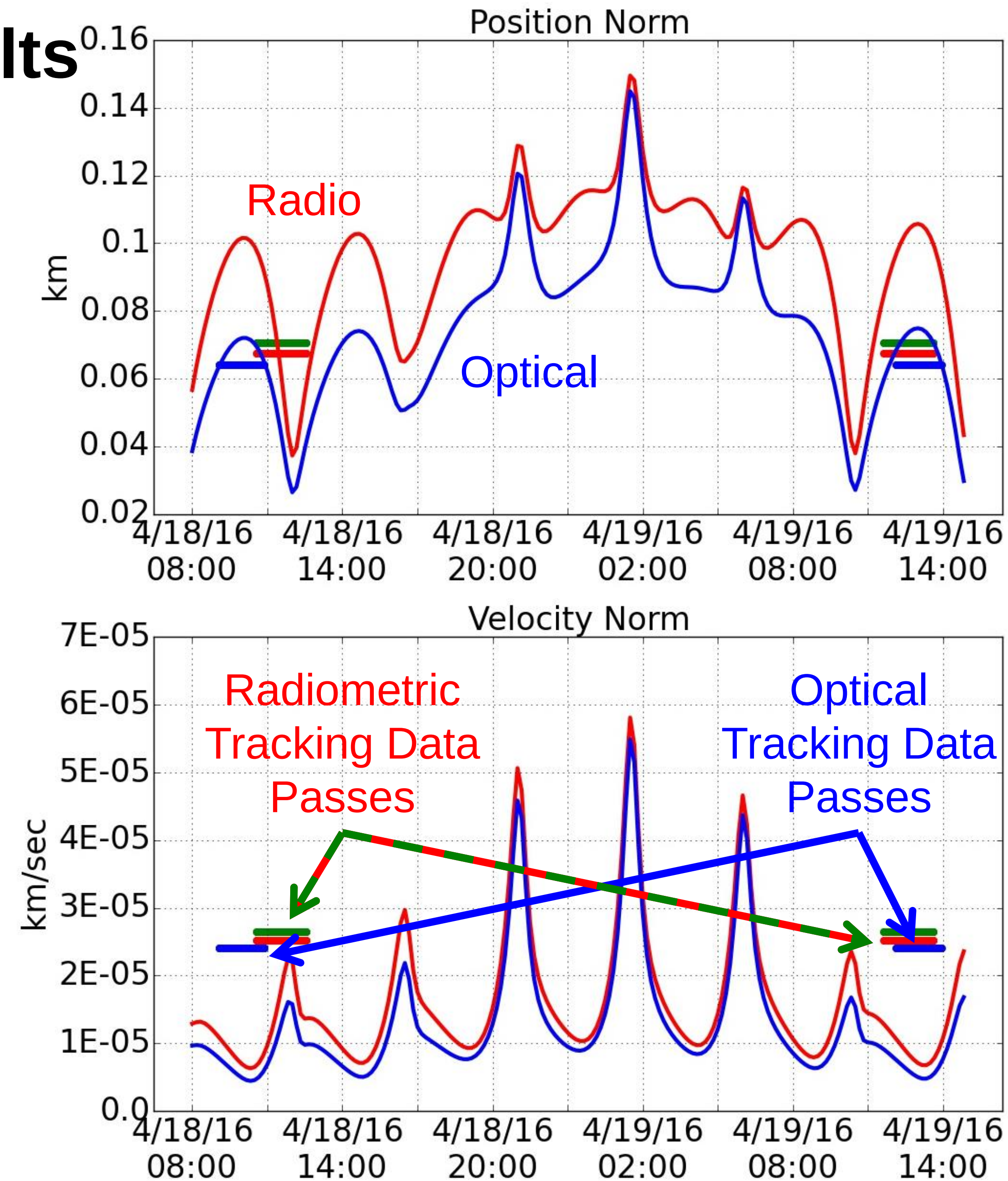
- Navigation performance most sensitive to telescope diameter



Credit: Sarah Elizabeth McCandless

Mars Orbiter Results April 18-19, 2016

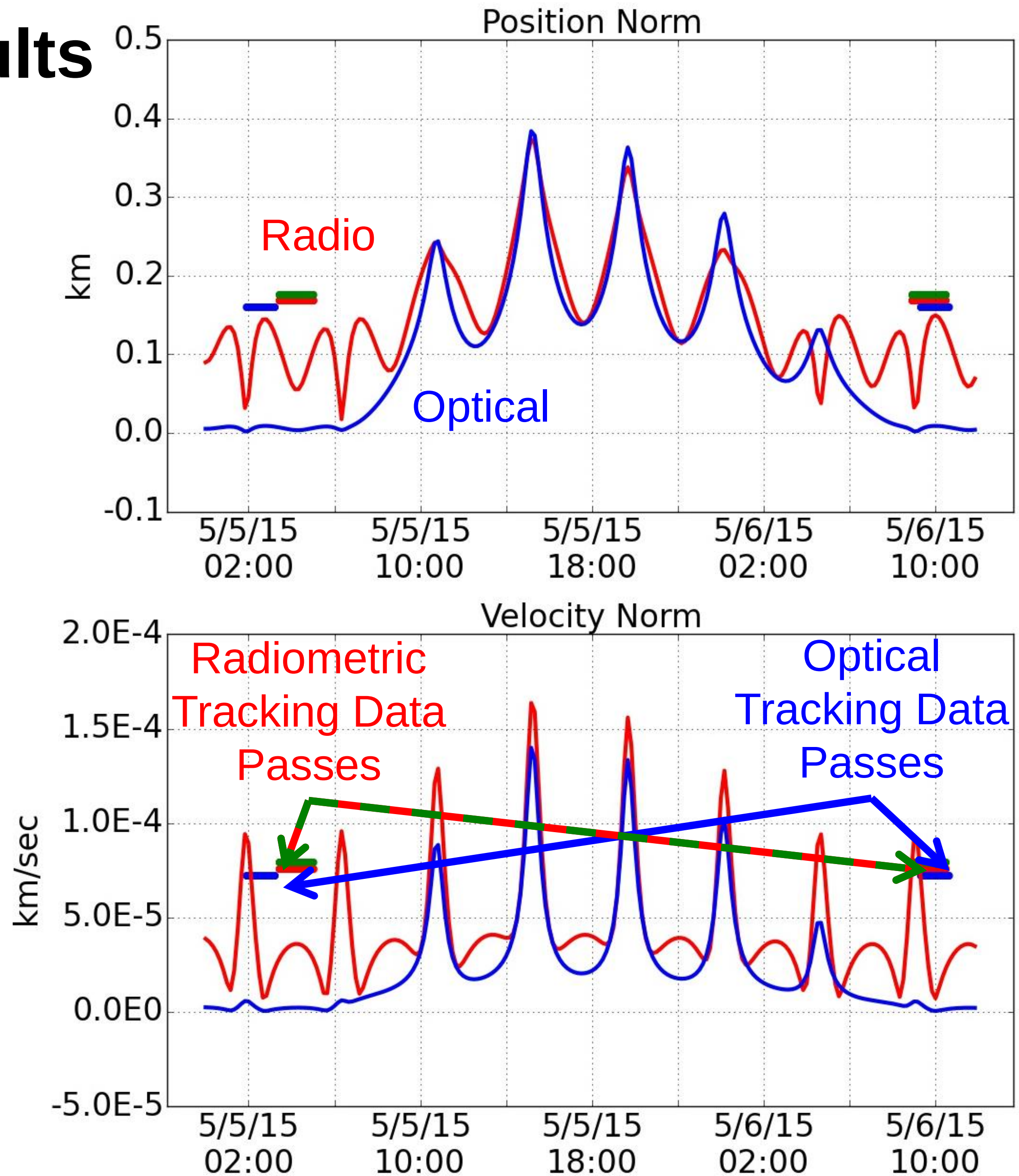
- Based on MAVEN, currently in orbit at Mars
- Reconstruct orbit to within 3.0 km
- Optical outperforms radio during tracking passes & tracking gaps



Credit: Sarah Elizabeth McCandless

Mars Orbiter Results May 5-6, 2015

- Degraded OD performance due to occultations
- Optical outperforms radio during tracking passes but not tracking gaps
- Still meets navigation requirements



Credit: Sarah Elizabeth McCandless

Other Navigation Scenarios to be Analyzed

- Asteroid rendezvous
  - Simultaneous imaging of spacecraft and target
  - Use of the on-board camera for target imaging
  - On-board autonomous navigation
- Mars spacecraft-to-spacecraft tracking
  - Complementing short-haul data links
  - On-board autonomous navigation
- Gravimetry of planets and moons

Conclusion

- Optical tracking has the potential to provide viable deep-space navigation data types with performance comparable to that achievable with radio.
- Optical tracking will be affected by some unique operational constraints that will limit its availability:
  - Could cover
  - Sky brightness for astrometry
  - Need for precise pointing – no optical LGA

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov